An Advanced Synthesized Ultra-Stable Oscillator for Spacecraft Applications[1][2]

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Abstract—Current ultra-stable oscillator (USO) technology relies on highly precise quartz resonators that are selected based on the desired output frequency and stability. These constraints on the crystal specifications significantly increase the lead time and expense of each USO. Recent research and development efforts in USOs by The Johns Hopkins University Applied Physics Laboratory (JHU/APL) have focused on a frequency synthesized USO based on a standardized, fixed-frequency resonator. The result of these efforts is a synthesized USO that will provide a frequency reference for transponders and other on-board users on future space missions. The frequency reference is stable enough for radio-science and navigation applications (Allan deviation $<1.5 \times 10^{-13}$ at $\tau = 10$ s), and is electronically adjustable to cover the entire deep-space communications band. This frequency agility allows in-flight re-assignment of the transponder frequencies. The synthesized USO offers low mass and DC power consumption yet maintains world-class noise performance and frequency stability performance.

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1. INTRODUCTION

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) has been developing spaceflight ultra-stable oscillators (USOs) for over 40 years to support a variety of applications, including timekeeping, navigation, communication, radar, and radio science. This paper describes a USO developed to support communications at Mars with the present generation of deep-space transponder. Since the deep-space communication bands are broken up into over 30 discrete frequencies and the transponder architecture requires the oscillator frequency to be a submultiple of the channel frequency, the oscillator frequency cannot be established until the communication channel is selected.

Furthermore, since the traditional USOs rely on harmonic multipliers to generate their output frequency, the quartz crystal resonator frequency specification is directly related to the communications channel selection. It is impractical to stockpile a sufficient number of USOs, or even resonators, to cover each communication channel, so the channel frequency must be assigned early in the program with no flexibility to change it during the hardware integration phase or in flight. With many missions planned to Mars, in-flight flexibility becomes even more desirable. Smaller spacecraft and robotic surface vehicles have also motivated a reduction in size, mass, and power.

The subject development effort incorporates frequency synthesis to provide flexibility and improves upon size, mass, and power of the current state of the art. A frequency source with a USO quality output that is also frequency synthesized has several benefits. Because resonators must go through a lengthy (and costly) screening process to select the best performing devices, it is impractical to screen and stockpile parts for every communication channel frequency. With a programmable frequency synthesizer, the resonator frequency can be standardized, for example, at 5 MHz. As this is a relatively common resonator frequency in the USO business, the parts are readily available in specialized, high-performance configurations. Furthermore, it becomes practical to maintain inventory of these resonators and

[1] "0-7803-8870-4/05/$20.00© 2005 IEEE"
[2] IEEEAC paper #1063, Version 10, Updated December 10, 2004

perhaps even a small inventory of the synthesized USO assemblies.

A second benefit of the synthesized output is a reduction in USO lead time. With the traditional USO and transponder system, there is a lengthy series process of mission design, frequency channel selection, resonator purchase, resonator screening, USO fabrication, and, finally, integration of the spacecraft. With a field-programmable USO output frequency, the resonator and USO tasks can occur in parallel with the mission design and frequency channel selection, greatly reducing the overall lead time.

Finally, with an in-flight programmable USO output frequency, there is greater flexibility in designing multiple missions in close proximity such as around Mars. NASA has several current and future missions to Mars, and probably more will be conceived. With a fixed turnaround ratio in the transponder and a common uplink frequency, the synthesized USO enables multiple downlink frequencies to be used for simultaneous tracking of multiple vehicles.

There is an ever-present demand for reducing size, mass, and power of electronic assemblies in spacecraft because of the huge per unit mass cost needed for launch. Accordingly, the trend toward smaller spacecraft and robotic lander vehicles compels the need to further reduce the USO size, mass, and power for unmanned exploration. Prior to this development effort, the lightest JHU/APL USO made had a mass of only 0.46 kg. This was achieved by the use of lightweight materials (titanium, magnesium, and aluminum) and the elimination of the DC-to-DC converter (for isolated power) typically included with our USOs.

2. DESIGN OVERVIEW

The design of the Synthesized Mars Technology Program (MTP) USO must provide an electronically adjustable output frequency, with high spectral purity and minimal DC power. The block diagram of the design, shown in Figure 1, addresses these design requirements by integrating an ultra-stable 5-MHz oscillator, a frequency multiplier, and a direct digital synthesizer (DDS). For the MTP USO we have integrated and adapted JHU/APL flight heritage technology as illustrated in Table 1.

Table 1. MTP USO Heritage

Technology	Heritage
DDS	New Horizons
Frequency multipliers, power converter, oven, and control	TOPEX, Mars Global Surveyor, Cassini, GRACE, CONTOUR

The 5-MHz crystal oscillator is based upon JHU/APL's extensive heritage of flight-qualified USO designs. The crystal is housed in an oven assembly that maintains the crystal at a temperature where the frequency of the resonator is least sensitive to small temperature changes. This ovenized crystal oscillator provides the ultra-stable, low phase noise reference for the X15 multiplier and field-programmable gate array (FPGA) clock.

The X15 multiplier accepts the 5-MHz input from the crystal oscillator and provides inputs to the DDS and the mixer in the up converter. The topology of the multiplier was chosen as an $A^* B$ topology, where A can be an integer from 2 to 6 and B can be any integer from 2 to 5. The flexibility provided by this topology allowed the multiplier design to progress in parallel with the synthesizer frequency planning. The conclusions of this frequency planning determined the 25-MHz clock rate of the DDS and the 75-MHz frequency of the local oscillator (LO) into the mixer. The multiplier also incorporates filters to provide 40-dB minimum suppression of all other undesired frequency products.

The phase noise performance of the synthesizer in this topology is driven primarily by the crystal oscillator phase noise and the degradation in phase noise caused by the frequency multiplication. The theoretical minimum degradation in phase noise due to multiplication is given as $20\log N$, where N is the frequency multiplication factor. Care is taken in the design of the multiplier stages to minimize further phase noise degradation in the multiplier.

A radiation-hardened FPGA provides a look-up table that maps the 34 transponder channels to the 32-bit word required by the DDS. The FPGA along with some additional analog circuitry also mitigates the effects of radiation on the DDS. The DDS frequency control word is reloaded periodically to correct for any changes in the DDS registers that may have been caused by a single event upset. If the DDS experiences latch up, the increase in current triggers the FPGA to reset the DDS. Finally, the FPGA provides the DDS with the frequency control word for the default channel as part of the power on initialization.

The DDS accepts the 25-MHz input from the multiplier and the frequency control word from the FPGA and provides a low phase noise tunable output frequency in the range of 1.4 to 1.8 MHz, with a nominal step size of 12.346 kHz, to the Intermediate frequency port of the mixer. Detailed discussion of the DDS operation is provided in Section 3. A center tapped output transformer is used to convert the differential current outputs into single-ended voltage output while maintaining good load balance to keep the spur level low. Since the DDS is a time-sampled system, a low-pass filter (LPF) is required to filter out the high-order alias terms. In this case, the alias term that is closest to the desired output is at (25 MHz − 1.8 MHz) 23.2 MHz, which is easily suppressed with a lumped element LC LPF.

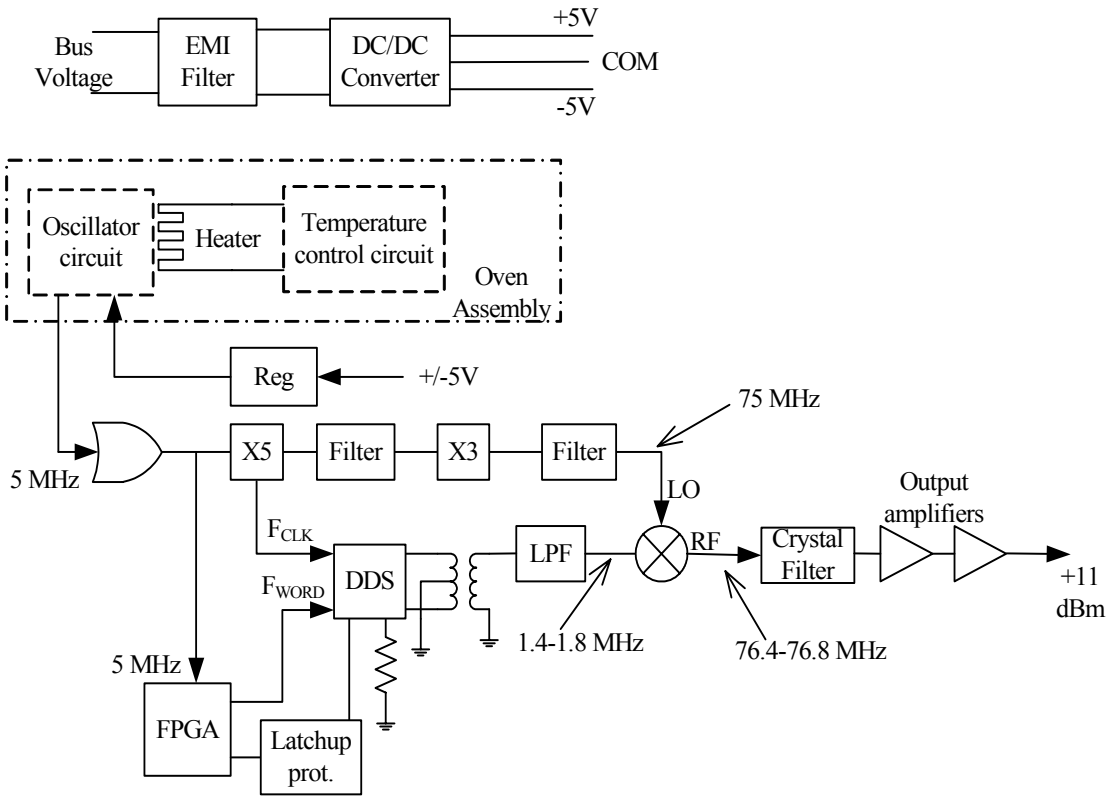

Figure 1. Synthesized MTP USO Block Diagram

The mixer and band-pass crystal filter form an up converter that translates the tunable output of the DDS to the desired frequency range of roughly 76.4 to 76.8 MHz. The band-pass crystal filter suppresses the undesired mixer outputs, which are the LO leakage at 75 MHz and the lower sideband in the range of 73.2 to 73.6 MHz. The output amplifiers are designed to provide the desired gain and signal level with minimal DC power consumption.

A power converter board accepts a spacecraft bus voltage in the range of 20 to 36 VDC and provides +5V and −5V outputs for the RF electronics. The power converter board uses a high-reliability, DC-to-DC converter and electromagnetic interference filter packaged in a microelectronic hybrid package for reduced size and mass. The DC-to-DC converter selected provides the highest efficiency among commercially available products and therefore minimizes the overall DC power consumption.

3. DETAILED DESIGN

Several technology developments were required to minimize the size, mass, and volume impact of the integration of a synthesizer with a standard USO. First, a low-power oven controller circuit was designed to provide a highly stable crystal oscillator temperature with the minimum DC power consumption. Then a lightweight packaging approach was developed to minimize size and mass while enabling in-air operation. Finally, a DDS-based up converter architecture was engineered to provide the required tunable output frequency with the minimum DC power and phase noise. These advances are the focus of our development effort.

Low Static Power Heater/Oven and Controller

The design improvements to the oven structure of the Synthesized MTP USO created from our effort were a combination of evolution from existing heritage concepts along with incorporation of certain novel approaches to circuits, materials, and mechanical structure. For example, the use of the low-power predecessor Planet B USO as a performance benchmark directed our design objectives toward refinement of its demonstrated advantages for frequency stability and the utilization of power. Neatly stated, any design concept introduced for the Synthesized MTP USO was tested against the Planet B USO's performance for size, power consumption, and frequency stability prior to its adoption into our development effort. This led to the retention of the oscillator sustaining circuit and the oven insulation and the preservation of the oven shape. In contrast, the need for operation at ambient air pressure, the effective use of regulated power from the switching DC-to-DC converter, and the circuit topology to provide both a digital multiplied clock and RF sinusoidal output required the introduction of new design approaches.

From the start, the requirement to minimize the power used for heating the oven, which provides the highly stable environment for the temperature-sensitive components of the Synthesized MTP USO's crystal oscillator, challenged our design concepts. Using the Planet B USO as a baseline, this requirement held us to less than 250 mW at 25°C in a vacuum environment of less than 5×10^{-3} torr. At the same time, the oven's temperature had to be tightly controlled to meet the required frequency stability of less than 4×10^{-11} over the operating environment of 0 to +40°C.

The general design approach to achieve this level of performance is to enclose the temperature-sensitive USO circuitry along with a very-high-gain temperature-control circuit inside a system of thermal insulation and conductive surfaces to form an extremely well insulated, isothermal structure. From the Planet B specifications, this meant that our effective thermal resistance had to be greater than 280°C/W over linear dimensions not exceeding 5 cm. As a comparison, the thermal resistance of still, dry nitrogen is about 40°C/W over a distance of a meter. A complication arises in the pursuit of this degree of thermal isolation in that the power dissipation of the crystal oscillator circuitry and the bias current of the temperature controller without any application of heater dissipation can quickly overwhelm the oven set temperature at moderately elevated operating environments. In the Synthesized MTP USO, great care was used to control this "static dissipation" to less than 120 mW, which nonetheless represents a significant portion of the power required to keep the oven at a set temperature of about +85°C at an operating environment of +25°C.

Figure 2 shows the measured oven power performance of the Synthesized MTP USO with changes in external operating temperature. In these measurements, the voltage supply of the oven is held constant at +28 VDC and temperature is changed from 0 to +40°C. Also, this measurement includes a 50-mW reduction in the static dissipation of the controller circuit through an improvement to its voltage regulation system. This power contribution is segmented between the power required to control the oven and the static dissipation of the circuit. This reduction indicates that there is just sufficient margin between the insulation factor of the design and the effect of internal heating caused by static dissipation. This further indicates the important balance between these two design aspects as degrading the insulation quality or "dragging" the oven would improve the margin for a higher temperature operating environment at the cost of degrading the oven's temperature stability by requiring more power.

The data of Table 2 and Figure 3 summarize the frequency performance characteristics of the Synthesized MTP USO obtained so far in our development. In Table 2, the total frequency change with operating temperature variation for the USO was about 2.6×10^{-11} or 0.65×10^{-12}/°C.

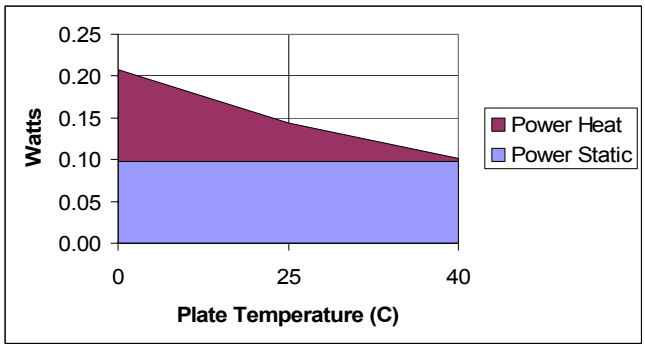

Figure 2. Measured Power Change with External Operating Temperature

Table 2. Frequency Change with External Operating Temperature

Plate Temp. (°C)	Delta Freq. (ppb)	Supply (V)	Power (W)
0.0	+0.0185	+28.25	0.1765
+25	0.0000	+28.25	0.1136
+40	–0.0074	+28.25	0.0503

Figure 3 is a chart of the dynamic or time variation of the USO's frequency stability. The Allan deviation method was used for measuring the fractional frequency deviation of the USO with time intervals of "tau" seconds at a constant temperature environment of +25°C. The two dominant characteristics of the time variation of a frequency source is its "flicker floor," related to the quality of the resonator, and its aging drift. In the data of Figure 3, the flicker floor of the USO is shown from 4 s to 40 s of tau while the aging drift extends outward from about 200 s of tau. In an ideal USO with no temperature dependence, these two characteristics would appear as the intersection of two line segments as shown. In the data of Figure 3, the temperature-dependent time variance can consequently be seen in the region of 40 to 200 s of tau approaching magnitudes of parts in 10^{-13}. This time-variant temperature dependence correlates to the frequency change observed in Table 2.

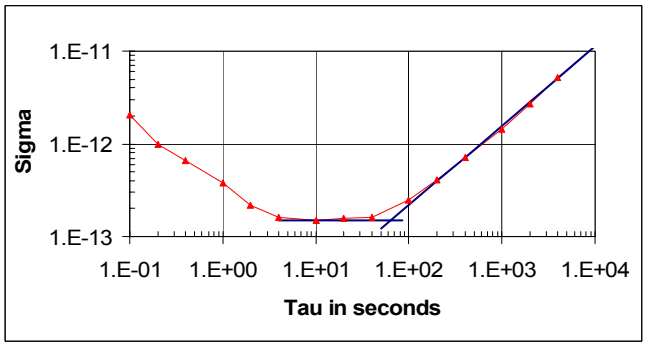

Figure 3. Allan Deviation Characteristic of the Synthesized MTP USO

Lightweight Packaging

The primary requirements for the packaging approach are to provide minimum size and mass. It was also desirable to have a packaging concept that would allow in-air operation and thus enable tests at ambient pressures that occur during spacecraft integration. In flight operation, or in a test vacuum environment, the power consumption of the oven is relatively low and is driven by the heat loss due to conduction and radiation. To operate in air, additional insulation or oven power is required to compensate for the increased heat loss due to the conduction of air. The goal of the packaging effort is to minimize additional oven power, or load to the spacecraft power bus, and additional size and mass for insulation.

Two additional guidelines were considered in the development of the packaging approach. First, maximizing the effective thermal mass of the ovenized oscillator will minimize the effects of thermal transients and therefore improve short-term stability. Second, minimizing the thermal gradient within the ovenized oscillator is necessary as described in the previous section. These goals, desires, and guidelines are somewhat conflicting and result in design and material trade-offs.

To quantify these trade-offs and establish the baseline design, JHU/APL conducted a material survey, evaluated package configurations with thermal models, and demonstrated selected configurations in hardware. The material survey evaluated the relevant properties of thermally conductive and insulating materials. For conductors it is desirable to have high thermal conductivity, high specific heat for high effective thermal mass, and low mass density. For an insulator the desirable properties are low thermal conductivity and low mass density.

Thermal models of various configurations provided valuable insight into the oven design and the impact of the material properties. Finite element models with defined boundary conditions were useful to visualize the large thermal gradients that were developed across the thermal insulating layers. Analytical models were advantageous for their abilities to predict effective thermal resistances and thermal transient responses.

An example of a thermal model prediction is shown in Figure 4. In this example, the required thickness of insulation to maintain the oven at +85°C with a +20°C (in-air) environment is calculated as a function of the DC power required by the oven.

Selected configurations were then realized in hardware to validate the models and demonstrate performance. One such demonstration was an oven with an insulation thickness of 0.35 in. (9 mm). From Figure 4, the expected DC power required to maintain the oven at +85°C was 1 W. The actual measured power was within 10% of the predicted DC power.

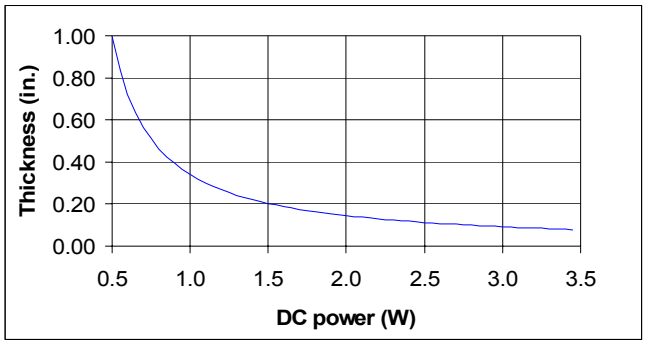

Figure 4. Required Insulation Thickness as a Function of DC Power

In-air operation was enabled in previous USO designs by the use of titanium Dewar. The Dewar is composed of two concentric enclosures separated by a vacuum gap. This vacuum gap provides very low thermal conductivity. Although the insulation is thicker than the Dewar is, the mass savings is more than 50 g.

An insight gained from our examination of materials for the requirement to minimize mass in the Synthesized MTP USO suggests that thermal performance could be enhanced by a reduction in the volume of the oven housing. Currently, investigation of this idea is constrained by the size of the quartz resonator enclosure. The size of the oven housing required to effectively control the temperature environment of the quartz resonator practically sets up the use of metal to reduce the impact of thermal gradient formation. However, if an enclosure for USO quality quartz resonators were available that reduced the current volume of 1.8 cm^3 by a significant fraction, the concern for thermal gradients would be reduced. The development of such a quartz resonator enclosure is an area for which JHU/APL is seeking technical collaboration with industry and funding sponsorship.

DDS Architecture and Modeling

Two frequency synthesis methods, phase-locked loop and DDS, were initially considered for the Synthesized MTP USO. The former derives its output from a voltage-controlled oscillator (VCO), which is locked to the 5-MHz crystal oscillator output. Within the loop bandwidth, the VCO noise floor tracks the crystal oscillator performance according to the frequency relationship. Outside the loop bandwidth, the VCO noise floor becomes the dominant noise level. After some investigation, it became apparent that a VCO was not available that could satisfy both the tuning range and noise floor specifications of our application. In contrast, the DDS looked promising for this application. Therefore, we began to focus on the details of the DDS method.

The DDS generates a sinusoidal amplitude waveform as a digital word and uses a digital-to-analog converter (DAC) at its output to create an analog waveform. Its output frequency is related to the input clock frequency and the frequency control word by:

$$F_{out} = F_{clk} * F_r / 2^N, \quad (1)$$

where F_{clk} is the clock frequency, F_r is the decimal value of the binary frequency control word, and N is the number of bits in the frequency control word. From Equation 1, the DDS can be viewed as an adjustable frequency divider. Its output signal noise floor is therefore better than the noise floor of the input clock based on the frequency dividing ratio, i.e., an improvement of $20*\log(F_{clk}/F_{out})$. However, since DDS is essentially a discrete time system, it naturally generates spurs in discrete frequency bins. The number of frequency bins from DC to F_{clk} is determined by the frequency resolution of the DDS output. Since trailing zeros in the binary frequency control word do not contribute to the DDS output signal phase increments, the output frequency resolution is inversely proportional to the width of the part of the frequency control word that excludes the trailing zeros [1]. The amplitude of the spur in each of the bins is determined by how well the sinusoidal waveform is replicated by the DDS architecture. In other words, the error in the DDS output, compared to a perfect sine wave, produces discrete spurious signals.

The spurious signals generated by the DDS can be separated into two categories: phase truncation spurs and amplitude error spurs. Because of technology limitation, the amplitude resolution in DDS is usually much lower than the frequency or, equivalently, the phase resolution. Thus, in practice, certain less significant phase bits are discarded in the DDS chip architecture when converting phase to amplitude. This truncating process generates phase errors and thus the phase truncation spurs. The number of phase truncation spurs is proportional to the amount of the discarded non-trailing-zero bits in the frequency control word F_r. Their frequency locations and levels are deterministic and independent of the DDS manufacturers' implementation [1]. On the other hand, the spurs generated due to amplitude errors are dependent on the implementation of the phase-to-amplitude conversion process as well as the DAC linearity and thus are not deterministic in general. The amplitude error spurs are more numerous and are spread out over the entire DDS output spectrum. A general rule of thumb for an ideal quantization process is that the power of all amplitude error spurs combined is $-6.02*D - 1.76$ dBc of the main output signal, where D is the width of the DAC.

Under some conditions, the DDS could also generate distinctively different spur patterns with the same frequency control word. This can occur when the phase states used for phase to amplitude conversion are not fully utilized or, equivalently, when the frequency control word uses fewer active most significant bits than the width of the phase bits used for phase to amplitude conversion. In the Synthesized MTP USO application, the challenge in selecting the frequency control words is to make sure the output frequency satisfies the accuracy requirement while (a) keeping the phase truncation spurs in the stop band of the output filter, and (b) preventing the conditions where a single frequency control word can generate different spur patterns. This means that the number of trailing zeros in the frequency control word must be large enough to satisfy condition (a) and small enough to satisfy condition (b).

In our application, the DDS is used as a frequency divider to generate the frequencies with the specified channel spacing at a lower frequency. This frequency is then mixed with a higher frequency tone to create the desired output. This arrangement is shown in Figure 1. The planning of the frequency scheme is based on several trade-offs. First, it is preferable to have a large F_{out} to F_{clk} ratio in the DDS so that it is easier to implement the LPF. However, the lower the F_{out} of the DDS, the harder it is to filter out the LO and the unwanted sideband after the up conversion. Therefore, based on the availability of the output crystal filter characteristics, the up-conversion frequency scheme was chosen with the LO at 75 MHz and the DDS output centered at approximately 1.6 MHz. Because both signals are derived from the same 5-MHz source, the theoretical noise floor of the LO signal should be approximately 33 dB higher than the DDS output signal; thus the noise contribution from the DDS chip is mainly due to the spurs within the pass band of the crystal filter. The second trade-off is at the selection of the DDS input clock frequency F_{clk}. As mentioned before, it is preferable to have a high F_{out} to F_{clk} ratio. However, with F_{out} already determined, a high ratio means having a high input clock frequency, which results in greater power consumption. Running the DDS with a 25-MHz clock results in 50-mW power savings compared to a 75-MHz input clock. The 25-MHz input clock to the DDS chip also provides increased isolation between the LO and intermediate frequency ports of the up-converting mixer. In addition, the anti-alias LPF is easily implemented with either a 25-MHz or a 75-MHz clock. As a result of these trade-offs, the DDS clock frequency of 25 MHz was chosen based primarily on the lower power consumption.

Circuit Implementation and Performance

The DDS uses a 32-bit-wide frequency control word and phase accumulator for advancing the phase of the output signal. We have selected our frequency control words to have either no phase truncation or one phase truncation spur approximately 9 MHz away from the main output. At the DDS output, the worst-case phase-truncation spur is approximately −80 dBc. This level is further reduced by the LPF. According to the DDS data sheet, the worst-case amplitude error spur level is −63 dBc, for a 1-MHz output frequency. In our test, the worst-case spur measured −75

dBc within the output filter bandwidth, with most of the other spurs less than −85 dBc.

A typical single-side band phase noise measurement of the up-converter output is shown in Figure 5. For this measurement, a commercial 5-MHz oscillator was used in place of the USO's 5-MHz oscillator. The large spur at approximately 1.5 MHz is an up-conversion product. The measured integrated double-side band phase error from 1 Hz to 2 MHz, excluding the LO spur, varies from 0.015° to 0.022° rms (root mean square) over the range of the 35 output frequencies. In benchmarking these results, we consider the possible application of the Synthesized MTP USO in a Ka-band transmitter. A 0.023° rms phase error in the USO output signal translates to approximately 0.1-dB degradation in Eb/No of a Ka-band phase modulated signal in a 2-MHz single-sided data bandwidth. This indicates that with careful application, the mix/multiply/DDS scheme can be used in low phase noise applications.

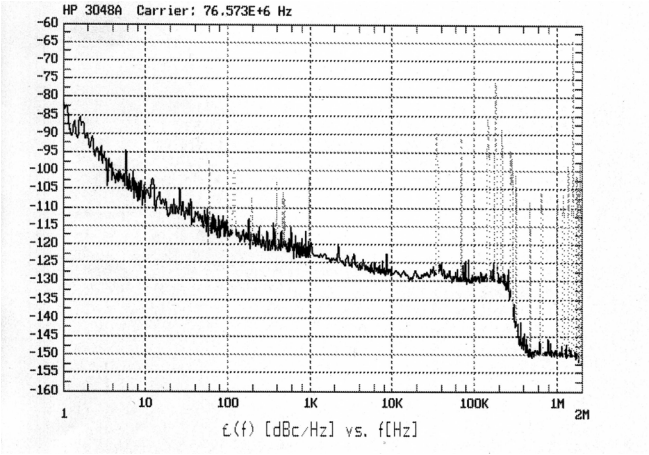

Figure 5. Typical Phase Noise at 76.57 MHz

Currently, the noise floor contribution from the X15 multiplier to the overall phase error is about 1 to 5 dB higher than the DDS spurs' contribution. With anticipated improvement in noise floor of the X15 multiplier board, it is conceivable that the DDS spurs could dominate in the phase error contribution. However, improvement in the DDS spur level is also expected. Empirically, we can select DDS frequency control words that satisfy our frequency accuracy goals that also provide the least spur contribution for a particular channel. In addition, it is possible to accelerate this control-word selection process using computer analysis if a specific set of DDS output spectrum can be obtained from the chip manufacturer [1].

4. PERFORMANCE COMPARISON

Table 3 provides a performance summary comparing several flight heritage USOs and the work presented in this paper labeled as MTP USO. Each USO listed in this table represents important milestones within the evolution of USO development at JHU/APL over the last 15 years [2]. In the case of TOPEX, a phase-locked loop frequency synthesizer was developed to track the excellent fractional frequency characteristics of the USO while generating two non-harmonically related output signals. The synthesizers of TOPEX were fixed such that they could not provide any frequency agility while in orbit [3]. For the USO's involved with the Gravity Recovery and Climate Experiment (GRACE), a smaller resonator and oven in a titanium Dewar flask were used with a conventional harmonic multiplier scheme. Currently, a slightly lighter version of this USO is being fabricated for use in the New Horizons mission to the Pluto-Charon system and is scheduled to launch in January 2006. A resolute attempt at conserving weight and power was realized in the Planet B USO for use in the Japanese Nozomi spacecraft with the condition that the USO could operate only in vacuum and with secondary power provided. Additional information on these and other flight heritage USOs can be found in Ref. 4.

Table 3. Performance Comparison of USOs over 15 Years of Development

Program	TOPEX **	GRACE	New Horizons	Planet B	MTP
Frequency synthesis	Y	N	N	N	Y
Power converter	Y	Y	Y	N	Y
In-air operation	Y	Y	Y	N	Y
Mass (kg)	3.0	2.2	1.5	0.5	0.6
DC power (W)	5.4	2.3	2.7	0.5	0.85
Phase noise @10Hz* (dBc/Hz)	−116	−112	−115	−118	−115
Stability at τ=10 sec	4.0×10^{-13}	2.0×10^{-13}	2.0×10^{-13}	3.0×10^{-13}	1.5×10^{-13}

*Scaled for 76 MHz carrier.
**Mass and power are sum of USO and synthesizer assemblies.

In comparison to these predecessors, the Synthesized MTP USO represents a high-performance frequency reference that provides in-flight programmable frequency synthesis, a compact mass-efficient design, low power consumption, and ambient air operation. In addition, our investigation into DDS architectures has shown that it is possible to pass the desirable signal integrity of a very low noise reference onto an array of closely spaced communication channels. The spurious content commonly observed in a DDS can be controlled from unduly contaminating these desired channels by the proper selection of the control word. Further, determination of this control word is quantifiable through a method based on the discrete Fourier transform [1].

5. SUMMARY

A synthesizer-based USO will enable in-flight re-assignment of transponder channels. In addition, the Synthesized MTP USO will allow the use of a standardized frequency resonator and a common USO design for all channels, thus enabling shorter USO lead times for the missions. Technology advances in low-power ovens, lightweight packaging, and DDS architectures have been incorporated into the USO design that will benefit a wide range of civilian and military applications.

REFERENCES

[1] S. Cheng, J. R. Jensen, R. E. Wallis, and G. L. Weaver, "Further Enhancements to the Analysis of Spectral Purity in the Application of Practical Direct Digital Synthesis," Proc. IEEE International UFFC 50th Anniversary Joint Conference, Montréal, Canada, August 2004 (to be published).

[2] J. R. Norton, J. M. Cloeren, and P. G. Sulzer, "Brief History of the Development of Ultra-Precise Oscillators for Ground and Space Applications," Proc. IEEE International Frequency Control Symposium, June 5–7, 1996, pp 47–57.

[3] M. J. Reinhart, "A Space-Qualified Frequency Synthesizer," Proc. IEEE International Frequency Control Symposium, May 28–31, 1991, pp 442–446.

[4] USO website: http://civspace.jhuapl.edu/technology/USO

ACKNOWLEDGEMENT

This research was conducted as part of the Synthesized USO (Ultra-Stable Oscillator) task for the Mars Technology Program sponsored by NASA/JPL for which the authors wish to express their appreciation.

BIOGRAPHIES

Robert E. Wallis *is currently supervisor of the Microwave Systems Section of the RF Engineering Group at JHU/APL. He received his B.S. from the Pennsylvania State University in 1980 and his M.S. from Villanova University in 1983, both in electrical engineering. He joined the JHU/APL Space Department in 1999 and is principal investigator for the Synthesized MTP USO project. From 1983 to 1999, Mr. Wallis was with EMS Technologies, Inc. (formerly Electromagnetic Sciences Inc.), where he managed the Microwave Integrated Circuit (MIC) design group and led the development of switch matrices and SSPAs for spacecraft applications, including C-band SSPAs for the TOPEX mission, X-band SSPAs for the Mars98 and Stardust missions, and Ku-band SSPAs for the International Space Station. From 1980 to 1983, Mr. Wallis was with General Electric Space Systems Division in Valley Forge, Pennsylvania, as a member of the MIC design group. His e-mail address is bob.wallis@jhuapl.edu*

Sheng Cheng *is currently a senior microwave circuit design engineer in the Microwave Systems Section of the RF Engineering Group at the Johns Hopkins University Applied Physics Laboratory. He received his B.S. from the National Taiwan University in 1982 and his M.S. from The Johns Hopkins University in 1989, both in electrical engineering. He joined JHU/APL's Space Department in 1997. Since then, he has been the lead engineer for the TIMED IEM Downlink Card and, more recently, the MESSENGER X-band SSPA. He has also been involved in the development of CONTOUR Uplink Down-Converter and the RF front end of the Digital Receiver IR&D project. From 1990 to 1997, Mr. Cheng was with the Whiting School of Engineering of The Johns Hopkins University. His work there involved the research and development of microwave circuit theory, design methodology, and measurement techniques. He also taught the microwave circuits classes in the Part-Time Engineering Program during that time and co-developed gEE-CAD, a microwave circuit CAD tool for instructional use. Prior to that, Mr. Cheng was with the LKC Technologies in Gaithersburg, Maryland, as an electronic circuit design engineer developing ophthalmologic electro-diagnostic equipment.*

Matt Reinhart *is currently supervisor of the Precision Systems and Radio Science section in JHU/APL's Space Department. In this role, he has overall responsibility for USO-related research and development at JHU/APL, in addition to the atomic clock ensemble that JHU/APL maintains. His section was responsible for developing the USOs for many successful military and NASA spacecraft. He received his B.S. from the University of Maryland in 1984 and his M.S. from The Johns Hopkins University in 1987, both in electrical engineering. He joined the JHU/APL Space Department in 1989, where he has designed a variety of RF and microwave electronic assemblies. Prior to working at JHU/APL, Mr. Reinhart designed solid-state microwave transmitters for the Westinghouse Electric Corporation.*

Gregory L. Weaver *joined the Senior Professional Staff of JHU/APL in 2003 as a member of the Space Department's RF Engineering Group. He is a technologist with extensive background in both the technical and business aspects of the frequency control industry and has held positions as a senior design engineer, technical manager, and marketing strategist over a 22-year career history, including Vice President positions with Bliley Technologies Inc. and the former Piezo Crystal Company. He received his M.S. in technology management from the University of Pennsylvania in 1993 and his B.S. in physics from Dickinson College in 1982. He is a licensed Professional Engineer in the State of Pennsylvania and a member of the IEEE and the UFFC Society. He has contributed frequently to a variety of technical conference proceedings, including the IEEE International Frequency Control Symposium and the European Frequency and Time Forum.*